

STRENGTH OF SOME CERAMIC SPECIMENS CONTAINING  
PARALLEL CYLINDRICAL HOLES

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## ABSTRACT

Ceramic specimens containing parallel cylindrical holes, arranged in symmetrical configurations, were loaded in compression to failure in the axial direction of the holes. The strength/weight characteristics of these specimens exceeded markedly those normally shown by ceramic specimens in which the corresponding porosity is uncontrolled as to pore shape and distribution. In general, the reduction in load-bearing capacity was directly proportional to the reduction in the cross-sectional bearing area, excepting in the low-porosity portion of the strength-porosity curve, where a larger strength reduction was shown.

## I. Introduction

An important objective in the utilization of ceramics as structural elements is the development of strong lightweight members. One obvious approach is to reduce bulk density by introducing pores into the material. However, it is well known that the introduction of randomly distributed pores of irregular shape causes a drastic reduction of strength with increasing porosity,<sup>1, 2</sup> as shown in Figure 4(a). This phenomenon is probably caused by internal stress concentrations and the reduction in effective area of material supporting the load; it also is influenced by the shape of the pores and their arrangement in the material.

The effect of the arrangement of the pores within the material was touched upon by Ryschkewitsch<sup>3</sup> in his results concerning the compressive strength of sintered alumina containing parallel pores. He noted that strength was greater for specimens tested with pores parallel to the pressure direction than for those with pores perpendicular to that direction. A logical reason for this phenomena is that the effective area of material supporting the load is greater in the former situation than in the latter. The research reported herein represents an effort to maximize the effective area by introducing cylindrical holes arranged in symmetrical configurations parallel to the loading direction, and to determine the effect of such controlled porosity upon the strength characteristics of the specimens.

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1. E. Ryschkewitsch, "Compression Strength of Porous Sintered Alumina and Zirconia," J. Amer. Ceram. Soc., 36 (2) 65-68 (1953).
  2. W.D. Kingery, Introduction to Ceramics, John Wiley & Sons, N. Y., p. 622 (1960).
  3. E. Ryschkewitsch, supra note 1.; also E. Ryschkewitsch and M.A. Schwartz, "Compression Strength of Sintered Alumina Containing Parallel Pores," WADC Tech. Note WCRR-53-14 (1953).

## II. Experimental

All specimens were prepared by slip-casting, employing a slip containing solids comprised of 50% aluminum oxide,<sup>4</sup> 20% feldspar,<sup>5</sup> and 30% clays,<sup>6</sup> and deflocculated with sodium-silicate. Plaster-of-Paris molds were used, each containing three bar cavities. Fourteen different rod assemblies, each composed of 1/8 inch drill rods and two drilled aluminum end-blocks, were inserted into the mold cavities. The slip was poured into the molds, while the molds were vibrated to ensure complete filling of the slip around the rods and to remove entrapped air. When the bars were in the "leather-hard" condition of dryness, they were removed from the molds and the rods withdrawn. Figure 1 shows a plaster-of-Paris mold which was employed, containing the removable rods.

The unfired bars were nominally one inch x one inch x eight inches. After drying, all the bars were fired together to 1400°C (at a rate of 75°C/hour), and held at this temperature for 48 hours. The apparent porosity of the fired material was  $7.7\% \pm 0.69$  (by ASTM CV20-46).

Figure 2 is a photograph of an end view (cross section) of each of the specimen types which were tested.

The fired bars were cut into specimens two inches in length, and the ends of each specimen were ground with abrasive powder. Each specimen was clamped in a steel holder for the grinding operation as an aid in developing parallel loading surfaces.

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4. Alcoa T-61 Alumina (-325 mesh tabular), Alumina Company of America, Bauxite, Ark.

5. Kingman Feldspar, Consolidated Feldspar Corp., Kona, N.C.

6. "ASP 900" Kaolin (15%), Minerals and Chemicals, Philipp Corp., Menlo Park, N.J.

"Bandy Black" Ball Clay (5%), Spinks Clay Company, Paris, Tenn.

"Champion & Challenger" Ball Clay (10%), Spinks Clay Company, Paris, Tenn.

The ends of each specimen were capped with a film of plaster-of-Paris; in addition, Garlock "900" gaskets (1/16 inch) were placed between the ends of each specimen and the platens of a compressive loading machine to assist in distributing the load. The compressive loadings were made in the axial direction of the holes using a loading rate of 12,000 psi/min.

### III. Results

All specimens failed with the material splitting into columns parallel to the direction of the compressive load. (See Figure 3.) The load-bearing capacity in compression of specimens containing no holes was  $47,500 \pm 2,400$  psi.

The compressive-testing results of 87 ceramic specimens are plotted as curve (b) in Figure 4; the points shown are average values. This curve of relative strength (i.e., the strength compared with the strength of the specimens which contained no holes) plotted against the percent of material removed from the specimens reveals that a rapid decrease in strength occurs until about 9% of the material has been removed. Additional removal of material results in a loss of strength which follows a straight line with about a  $45^\circ$  slope. Extrapolation of this line to zero strength gives a value of 78.5% material removed; this value coincides with the amount of material which would be removed if all holes were just touching each other so that the specimen would fall apart.

### IV. Discussion

Several factors relating to the load-bearing capacity of the test specimens will be considered.

(a) The most obvious contributing factor affecting strength is the decrease in the effective cross-sectional area of the specimens. Unlike a system which contains a random distribution of pores whereby the effective cross-sectional area diminishes more rapidly than the decrease in density, the ratio of the reduction of the effective cross-sectional area of these

specimens (containing cylindrical holes) to the decrease in density is 1:1. Consequently, all material within the specimen is load-bearing when the load is applied in the axial direction of the holes.

If the decrease in effective cross-sectional area of the specimens were the only effect to be considered, then a  $45^{\circ}$  line -- curve (c) in Figure 4 -- would be the expected curve. With greater than 9% of the material removed, the experimental curve (b) is parallel to this line, indicating that the net effect of the other mechanisms which contribute to strength degradation remains constant for material removals within this range.

(b) Recently, Daniels and Moore<sup>7</sup> reported that the presence of artificial surface flaws in a porcelain ceramic caused a drastic decrease in strength when the number of flaws were few and sparsely located, whereas subsequent increases in the density of the flaws resulted in corresponding increases in strength. This result was explained by the theory of stress interaction effects of proximate notches, whereby the stress which would be concentrated at a single notch is distributed throughout other notches which are located in the vicinity.

This effect probably also is met with in the present study, since the holes may be expected to cause stress concentrations. With only a few widely separated holes, stress interaction would be slight and the stress concentration effect would tend to reduce strength significantly. When the number of holes is increased, interaction of stresses should reduce their concentration, so that the resulting decreases in strength are less.

(c) Since the material failed by splitting into columns oriented in the direction of the applied load, there is the possibility that a cylindrical hole, if in the path of a propagating crack, may allow for crack termination.

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7. W.H. Daniels and R.E. Moore, "Fracture Behavior of a Model Brittle Solid Containing Artificial Surface Flaws," J. Amer. Ceram. Soc., 48 (5) 274-75 (1965).

Such arrestment of crack propagation at a hole would appear to be enhanced for specimens with more than a few holes.

#### V. Conclusions

These results confirm that substantial improvements in the strength/weight ratios of ceramics are possible by controlling the shape and geometry of pores in the material. For ceramic specimens containing cylindrical holes in symmetrical configurations, and oriented parallel to the direction of compressive loading, the strength/weight characteristics have been shown to greatly exceed those for ceramics where porosity is uncontrolled. It also was observed that the presence of a few cylindrical holes caused a larger corresponding reduction in strength than when subsequent additional holes were introduced, which may be interpreted in terms of stress-concentration effects.

#### Acknowledgment

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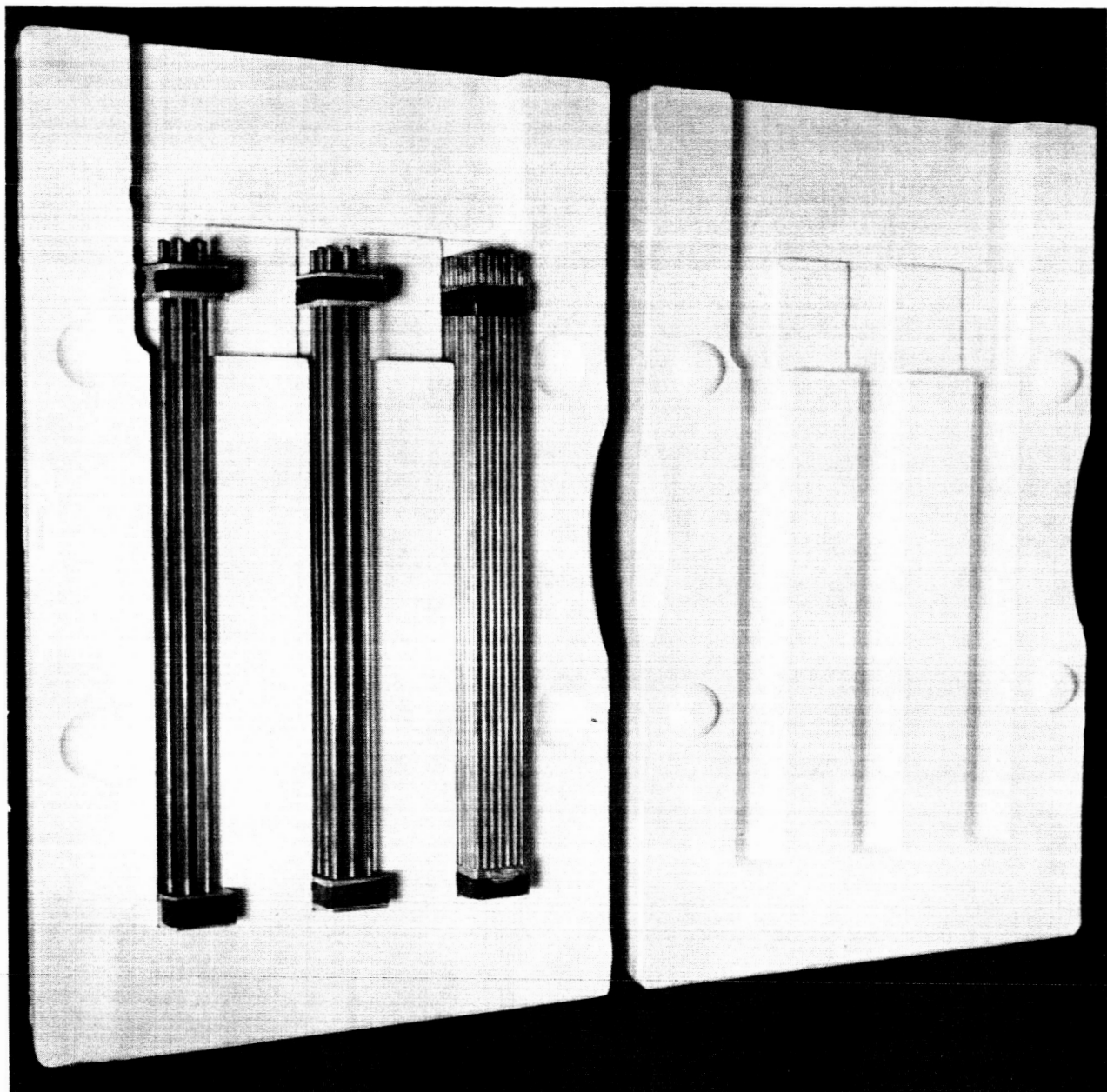
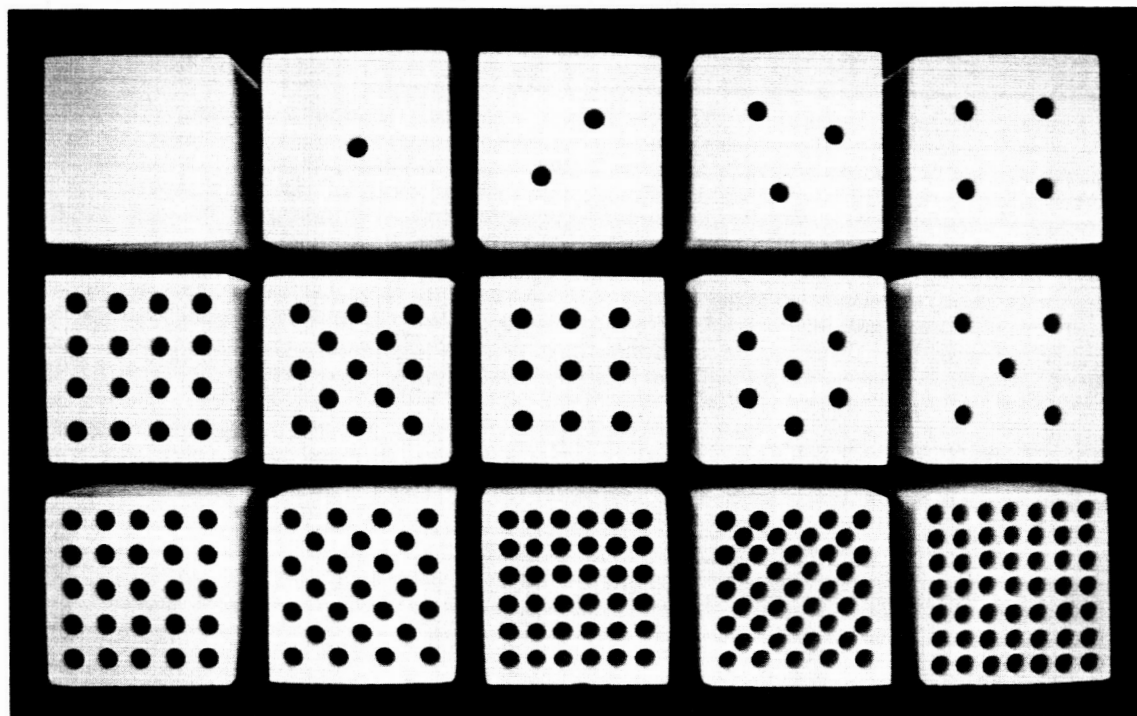


Figure 1. Mold, with Removable Rods





1	2	3	4	5
10	9	8	7	6
11	12	13	14	15

Figure 2. Ceramic Specimens Containing Cylindrical Holes

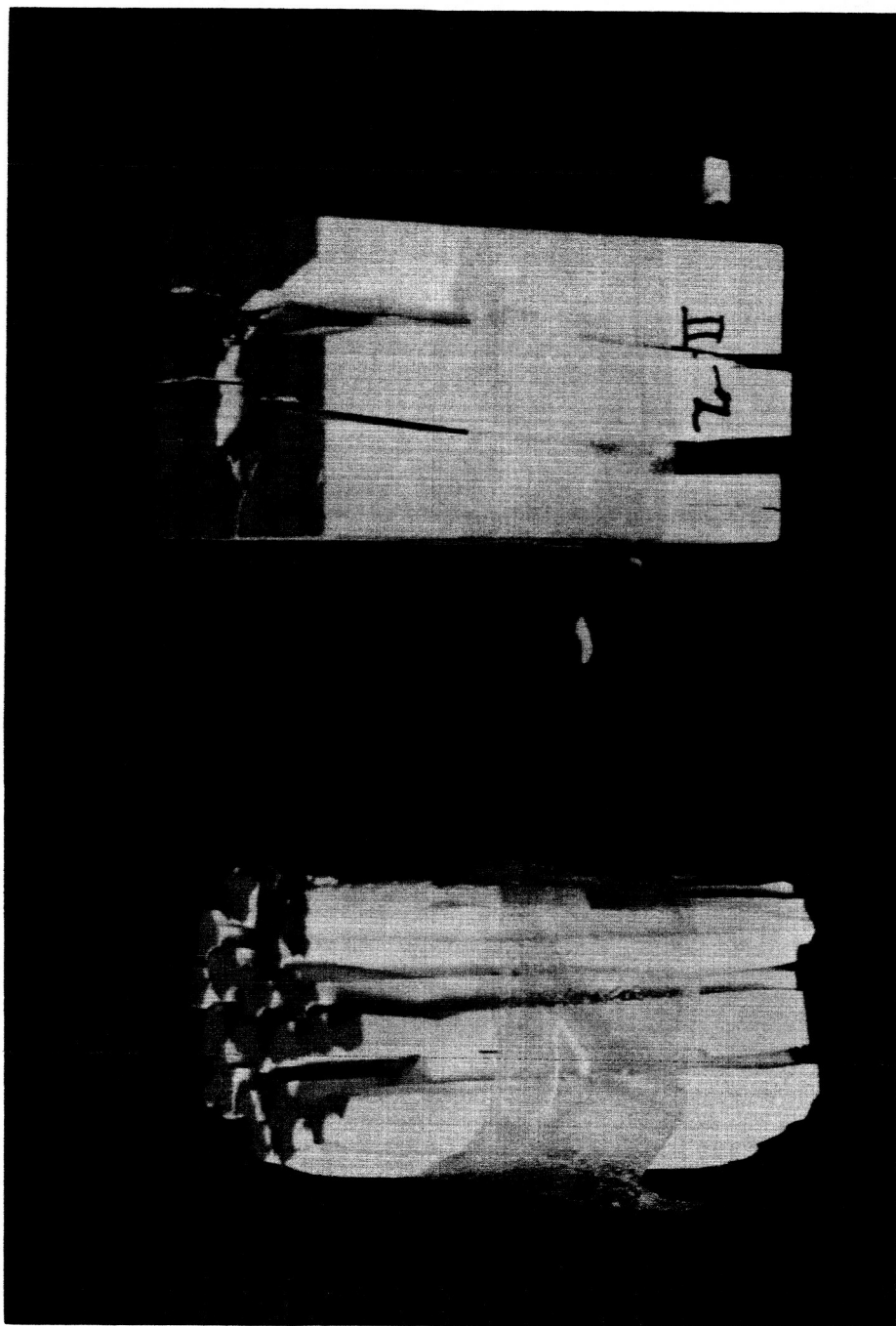


Figure 3. Specimens Showing Typical Nature of Failure

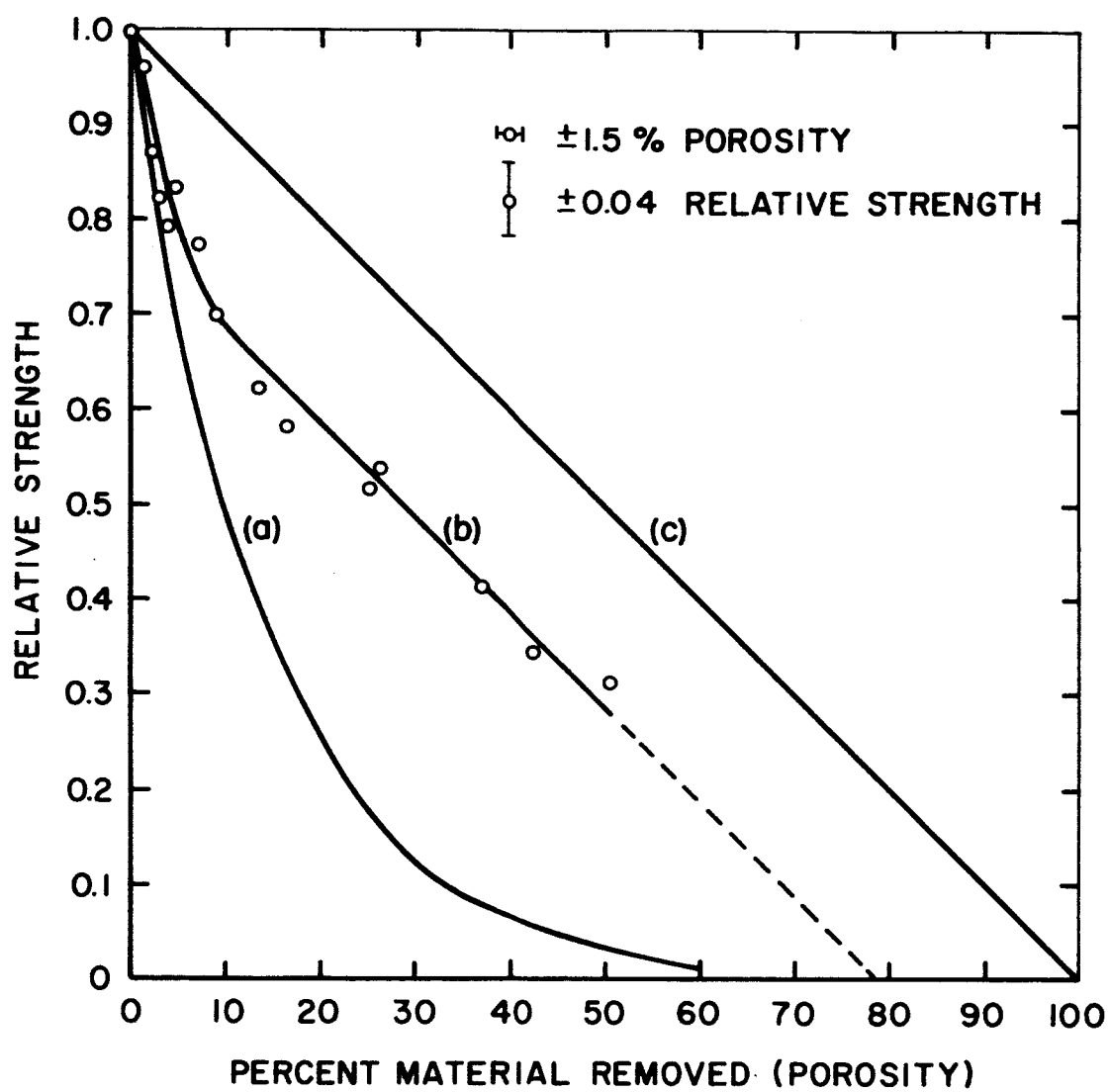


Figure 4. Compressive Strength of Ceramics Containing Several Types of Pores